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LAWRENCE LIVERMORE NATIONAL LABORATORY'S NUCLEAR CRITICALITY AND REACTOR PHYSICS EXPERIMENTAL TRAINING ASSEMBLIES AND ACTIVITIES

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ABSTRACT

Lawrence Livermore National Laboratory's (LLNL) Nuclear Criticality Safety Division has extensive experience deploying hands-on training to experimentally demonstrate criticality, neutron multiplication, and reactor physics concepts. LLNL has taught the U.S. Department of Energy's Nuclear Criticality Safety Engineer Hands-on Training Course for ten years using the Training Assembly for Criticality Safety (TACS). The TACS is a subcritical assembly composed of eight nesting hemishells of 93% enriched uranium that fit together to form a 23 kg sphere with a central cavity. Using the "Approach to Critical" experimental method, the effects of mass, moderation, reflection, separation distance, operator hands, and neutron poisons are demonstrated to the students through hands-on laboratory work.

Following de-inventory of high security materials from LLNL, the TACS was transferred to a secure facility in Nevada and a new subcritical assembly for training and detector development purposes was designed and built at the Livermore site. The new assembly, the Inherently Safe Subcritical Assembly (ISSA), uses up to nine modified surplus MTR type fuel arranged in a square lattice in a water tank. Each assembly contains nineteen curved plates with 232 grams of ^{235}U of highly enriched U_3O_8 dispersed in a matrix of aluminum and fully clad in aluminum. Current hands-on experiments with ISSA include approach to critical by mass (number of assemblies) and moderator height, demonstration of detector placement effects, effect of core shape on leakage, and measurement of buckling and extrapolation length.

In the near future LLNL, in partnership with the Institut de Radioprotection et de Sûreté Nucléaire at Fontenay-aux-Roses, France, is planning to develop a fundamental physics subcritical multiplicity benchmark for ISSA at three or more levels of subcritical multiplication for publication in the International Handbook of Evaluated Criticality Safety Benchmark Experiments.

1. Introduction

This paper will describe two unique training assemblies at LLNL, the TACS and ISSA, used to demonstrate concepts of criticality, neutron multiplication, and reactor physics. The TACS was used extensively as a training aid for fissile material handlers, criticality safety engineers, managers, and regulators at LLNL since 1979. De-inventory of high security materials at LLNL was completed in September 2012, which required transfer of the TACS to the Nevada National Security Site (NNSS), where it is still used for national hands-on criticality safety training. Consequently, the Nuclear Criticality Safety Division at LLNL decided to build a new subcritical assembly for training and detector development purposes that could be conveniently utilized by laboratory researchers, visiting scientists and students in a low security environment at the main laboratory site.

2. Training Assembly for Criticality Safety

During the 1950's and 1960's, LLNL did many critical and subcritical experiments to provide basic validation data for its computer codes. The Nimbus program used a set of nesting highly enriched uranium (HEU) hemishells at 93.15% enrichment [1]. In 1979, a training assembly was created for use with eight of the Nimbus shells to aid in on-site LLNL Fissile Material Handler (FMH) training [2]. The eight Nimbus shells fit together to form a 23 kg sphere with a central cavity. The outer radius of the HEU is 7.925 cm. Lucite (acrylic, $C_5O_2H_8$) moderators of varying thicknesses can be placed inside the cavity and hemispherical Lucite reflectors of varying thicknesses can be fit on the outside of the assembly. The TACS is assembled on an assembly table that can be raised and lowered by means of a hand crank (Figure 2).

Figure 1: Eight HEU shells (left) and four nested shells that form lower half of the assembly (right).

Fig. 2. The Training Assembly for Criticality Safety, shown with a 3" gap separating the hemispherical halves.

2.1. TACS Experimental Method

The TACS is a subcritical assembly that achieves a maximum multiplication of approximately 10, corresponding to an effective multiplication factor (k_{eff}) of about 0.90. The assembly is driven by a neutron source to quickly obtain meaningful count rate data with ^{3}He neutron detectors.

Laboratory experiments [3] follow the "Approach to Critical" experimental method. For Approach to Critical by fissile mass, for example, the students begin by building a non-multiplying assembly using depleted uranium (DU) shells reflected and moderated by Lucite. A count rate measurement is taken, which determines the baseline of unmultiplied source neutrons emitted from the assembly. One DU shell is replaced with a similar amount of HEU and another count rate is taken. By dividing this second multiplied count rate by the baseline unmultiplied source count rate, corrected for background neutron counts, an experimentally observed multiplication, M_{obs}, is determined. By plotting $1/M_{obs}$ versus the fissile mass and linearly extrapolating to the point when $1/M_{obs}$ reaches zero, an estimate of the fissile mass needed to achieve criticality can be made. An example of an Approach to Critical, or 1/M, curve, with data from the TACS, is shown in Figure 3.

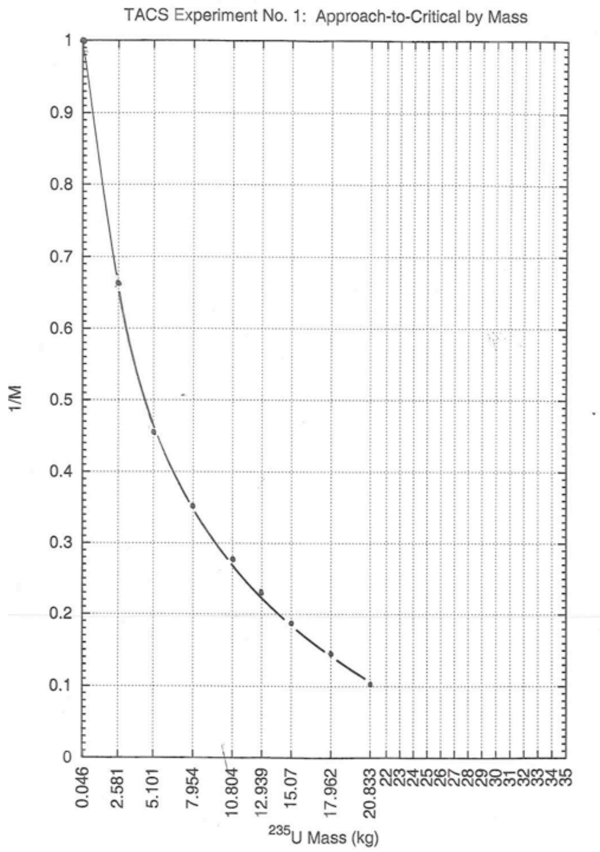

Fig. 3. Approach to Critical by Fissile Mass Curve. Critical was estimated to be 28 kg of ^{235}U mass by extrapolation to the X-intercept.

The TACS assembly was designed to be highly versatile and demonstrate many of the parameters that affect nuclear criticality. Six experiments are completed during the laboratory: Approach to Critical by Fissile Mass, Approach to Critical by Lucite Moderation, Approach to Critical by Lucite Reflection, Approach to Critical by Separation Distance, Effect of Reflection by Operator Hands, and the Effect of Neutron Poisons.

2.2. TACS Utilization

The TACS was originally designed to train LLNL FMHs in an experimental basis for the parameters that affect criticality. It was used for this purpose from 1979 until the late 1980s.

In 2006, the US Department of Energy's Nuclear Criticality Safety Program Manager requested that LLNL begin offering a hands-on criticality safety training course to Nuclear Criticality Safety Engineers during the relocation of the Los Alamos National Laboratory (LANL) Critical Experiments Facility at TA-18 to the NNSS. In 2012 the TACS was also relocated from LLNL to a secure facility at the NNSS. LLNL continues to provide the training in conjunction with LANL at the NNSS.

Based on the many years of data accumulated during the conduct of the class, a paper was written that gave an experimental basis for quantifying the effects of operator hands on a fast metal system [4].

3. Inherently Safe Subcritical Assembly

3.1 Design Considerations for ISSA

Inherent safety, accessibility, low cost, and simplicity were major considerations identified during conceptual design. The fuel design concept was to use encapsulated fuel to avoid need for establishing a contamination area. Furthermore, the intrinsic radiation present in the fuel and external neutron sources should be strong enough to enable meaningful multiplication measurements within reasonable count times while weak enough to avoid establishing a radiation area and requiring associated controls. The amount of fuel should be limited to preclude any credible risk of a criticality accident. These inherent safety features identified during conceptual design inspired the name Inherently Safe Subcritical Assembly (ISSA). From the outset, the LLNL design goal was to enable a "hands on" student experience rather than student observations of a demonstration by a qualified or licensed operator.

Most importantly, the fuel "attractiveness level" should be as low as possible to minimize security requirements and enable easy access to persons without security clearances including university students. To minimize costs, surplus materials were used wherever possible.

Simplicity of operations led to consideration of highly enriched uranium fuel in order to minimize the size of the assembly. Furthermore, it was recognized that bundling the fuel elements into subassemblies could minimize the number of fuel handling operations enabling rapid fueling and defueling operations. A literature review led to a design concept of using surplus encapsulated un-irradiated highly-enriched uranium Materials Test Reactor (MTR) type fuel assemblies supported in a simple lattice structure within a cylindrical tank for moderation by water as illustrated in Figure 4, which shows a lattice of SPERT-D fuel elements used in critical experiments at Oak Ridge National Laboratory in 1964-1965 [5].

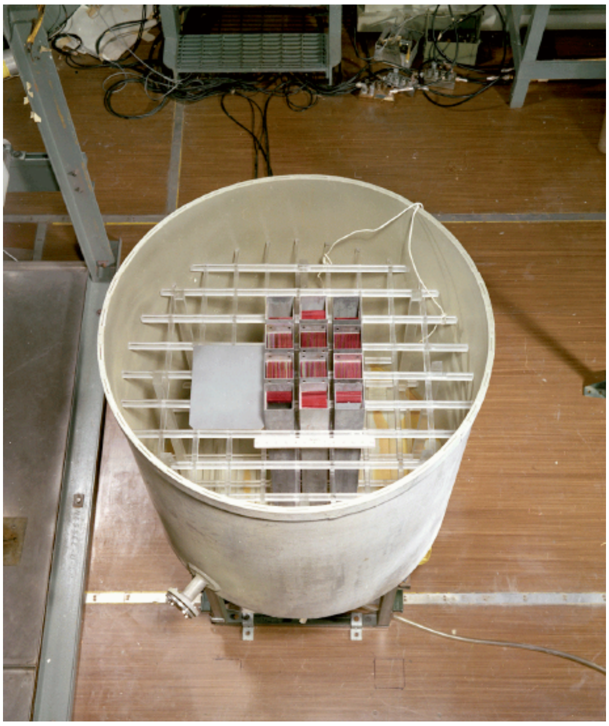

Figure 4. Design Concept

Two other conceptual design considerations included the desirability of installing a core tank much taller than the active fuel length to enable measurements of higher harmonic flux effects and to elevate the tank above the floor to enable access to the tank bottom for placement of neutron sources away from student handlers and to enable source jerk measurements. An elevated tank is a design feature we noted in the DELPHI [6] subcritical assembly and the Jordan Subcritical Assembly [7].

3.2. ISSA Final Design

The final design realized uses up to nine modified surplus MTR type fuel assemblies from the Omega West Reactor (OWR) [8] manufactured by the Naval Nuclear Fuel Division of Babcock & Wilcox (B&W) in Lynchburg, Tennessee, USA. Each assembly contains either 220 or 232 grams of ^{235}U of highly enriched uranium within nineteen curved plates containing either 11.5 or 12.2 grams of ^{235}U in U_3O_8 dispersed in a matrix of aluminum and fully clad in pure aluminum. These assemblies were significantly reduced in size by LLNL to an approximate length and weight of about two feet and twelve pounds for ease of handling. LLNL modified the original assemblies by removing the aluminum end pieces (i.e., the "nozzles" used in the Omega West Reactor for fuel positioning and handling) and fabricated new aluminum fixtures for the top and bottom of the fuel elements to aid in their placement into the lattice array. Photographs of an OWR fuel assembly modified by LLNL are provided in Figure 5.

With 9 fuel assemblies arranged in a water tank, the subcritical assembly has a peak multiplication of approximately 20.

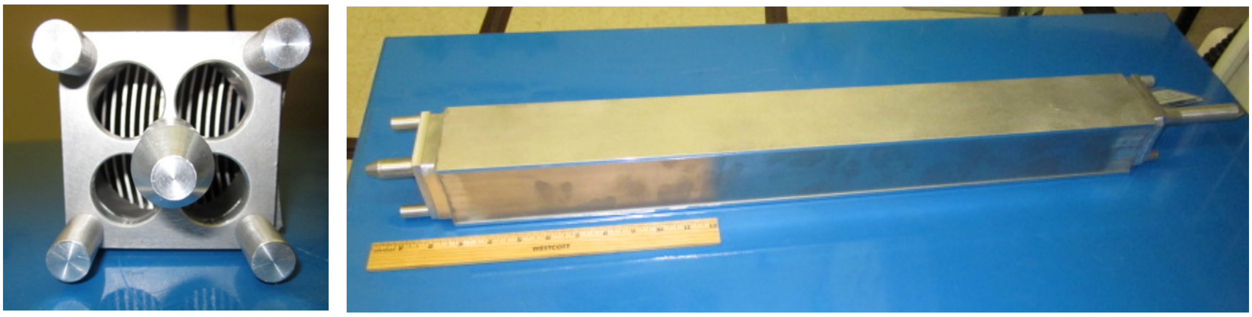

Figure 5. LLNL Modified OWR Fuel Assembly

The design layout of the ISSA is shown in Figure 6. The core tank, shown as the dark gray cylinder in the center of the platform, is a surplus tank used previously for chemical etching. The water dump tank, shown as the white tank to the right of the platform, was previously used on a truck bed for cleaning up large wastewater spills. The overhead crane was excess equipment from another facility. The stairs, railings, platforms and their supports were taken from surplus office trailers.

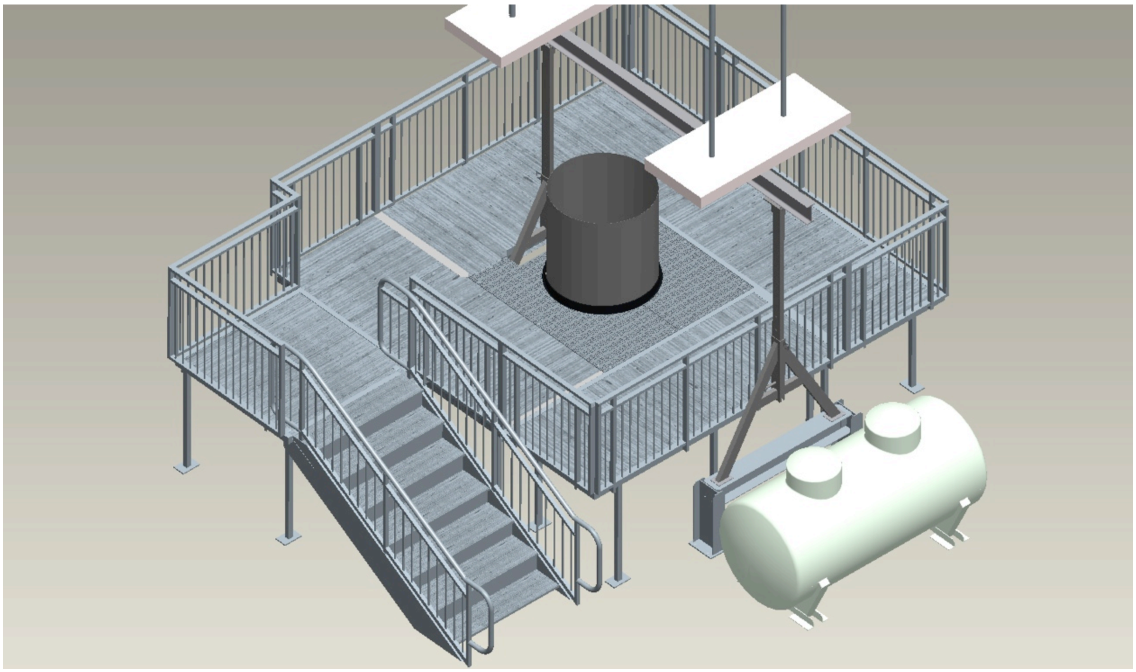

Figure 6. Design Layout of the ISSA

Other repurposed items were ^{3}He detectors taken from health physics survey instruments and eight large ^{3}He detectors recovered from an obsolete multiplicity drum counter. Several 110-gallon DOT-6M/2R obsolete shipping containers were also obtained for fuel assembly storage. Major parts fabricated by LLNL include the tank support stands and seismic restraints, detector tube wells and their supports and the aluminum core lattice. LLNL also fabricated all aluminum "mock fuel" assemblies to original B&W manufacturing drawings. These assemblies are useful in establishing an unmultiplied base count rate for subcritical multiplication measurements. Minor procurements included a water pump and associated piping and controls, drum storage racks and locking drum lids. Eberline model E-600 detectors are used to power and record counts with the small ^{3}He tubes and the large ^{3}He tubes are used with prototype Fission Meters for multiplicity counting. These detectors and ^{252}Cf sources are on loan from other laboratory programs. A photograph of the ISSA "as built" configuration is provided as Figure 7.

Figure 7. ISSA "As Built" Configuration

3.3 ISSA Utilization

The ISSA was designed as a training aid and as a multiplying assembly for the development of detectors including multiplicity detectors such as prototypes for the LLNL-designed ORTEC Model FM-P3 Fission Meter and next generation detectors. As a training aid for the fundamentals of subcritical reactor physics, the syllabus given in Table 1 was as originally envisioned in 2011-2012. Those subjects of the syllabus actually completed and ready to teach are indicated with a check mark. Use of ISSA as a training aid for safeguards measurements is also under consideration.

ISSA was authorized for use on September 7, 2012 and the first approach-to-critical was completed on September 13, 2012 with typical inverse multiplication curves determined by student measurements as shown in Figure 8. Note that the estimated critical number of ISSA fuel assemblies by extrapolation of inverse multiplication measurements is 11, which is in excellent agreement with safety calculations completed in COG10 [9].

Table I. Syllabus

Lectures	Experiments
Basic physics • Inherent sources of neutrons • External neutron sources (^{252}Cf) • Neutron cross sections ✓ Physics of chain reactions • Diffusion and Fermi age theory ✓ Modified one group diffusion equation ✓ Neutron kinetics equation • Statistics of chain reactions Hand calculations • Six factor formula ✓ Diffusion constants ✓ k-infinity, migration area and buckling ✓ Nucleonics data sheet no. 38 ✓ Alpha, k_{eff}, reactivity • Count distributions and Feynman-Y Computer codes ✓ RHEINGOLD (Diffusion) [8] ✓ ARDRA (S_N) ✓ COG (Monte Carlo)	Source multiplication experiments ✓ 1/M vs. mass (or number of assemblies) ✓ Detector placement effectors ✓ Source effects ✓ 1/M vs. moderator height • 1/M vs. pitch • Effect of over/under/optimum moderation • Effect of isolation by water • Effect of neutron poisons (including flux traps and control rods) • Effect of reflector materials ✓ Effect of core shape on leakage • Temperature reactivity coefficient • Fuel reactivity coefficient • Void reactivity coefficient Dynamic experiments • Source jerk • Pulse die-away ✓ Feynman-Y Spatial methods ✓ Buckling and extrapolation length

In the near future LLNL, in partnership with the Institut de Radioprotection et de Sûreté Nucléaire at Fontenay-aux-Roses, France, is planning to develop a subcritical benchmark for ISSA at three or more levels of subcritical multiplication for publication in the International Handbook of Evaluated Criticality Safety Benchmark Experiments. Measured count distributions at the highest level of multiplication attainable in the current design were completed in 2014 to demonstrate feasibility. Typical list mode data for a count distribution and Feynman-Y fit are shown in Figure 9. Preliminary analysis results indicate a multiplication of about 22.5 corresponding to keff = 1 – 1/M = 0.955 [10].

4. Conclusions

LLNL has a long history of developing and deploying unique hands-on nuclear training assemblies. After de-inventory of the LLNL site and relocation of the TACS to the NNSS, ISSA was developed at low cost as an institutional laboratory asset and is inexpensive to maintain. ISSA is available for "hands on" training and as a multiplying assembly for detector development. Due to inherent safety by design, students and visitors to the laboratory are authorized to handle the fuel, operate the detectors, water pump, etc., and execute all measurements under supervision. The only student prerequisites are General Employee Radiation Training, which is a read and sign instructional booklet that can be completed prior to visiting LLNL, and a pre-job briefing in the ISSA laboratory on the hazards and controls specified in the authorization basis.

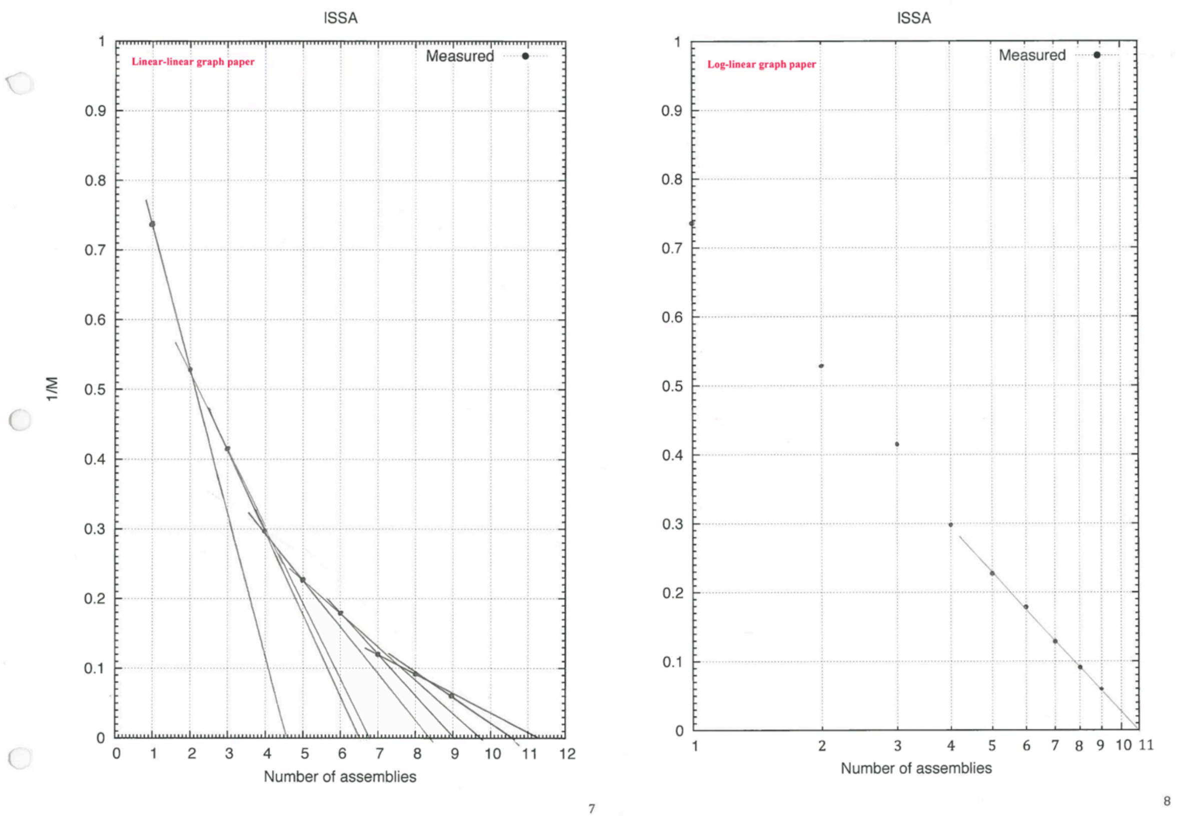

Figure 6. Typical Inverse Multiplication (1/M) Curves

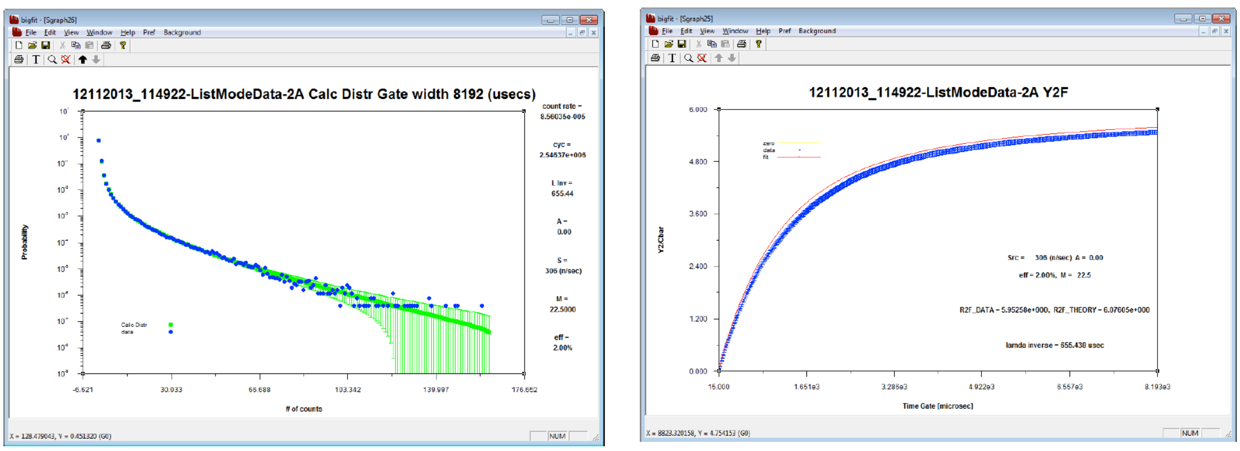

Figure 7. Typical Measured Count Distribution and Feynman-Y Fit at M=22.5

5. Acknowledgments

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